

STATUS OF KASKA: THE JAPANESE REACTOR $\sin^2 2\theta_{13}$ PROJECT

F.SUEKANE (for the KASKA Collaboration*)

suekane@awa.tohoku.ac.jp
Research Center for Neutrino Science,
Graduate School of Science, Tohoku University,
Sendai, 980-8578, Japan

Last year, in the NOON03 conference, we pointed out the importance of reactor $\sin^2 2\theta_{13}$ measurement and showed a realistic experimental idea to measure $\sin^2 2\theta_{13}$ precisely using world's most powerful reactor complex. Since then, the conceptual design of the experiment and negotiations with electric power company, have been progressing. In this proceedings for the NOON04 conference, the present status of the proposed experiment, now called KASKA, is described.

1. Introduction

Since neutrinos have peculiar properties such as very small masses, very much different mixing patterns from quark sector, possibility of being Majorana particle, study of neutrinos is very important to understand the nature of the elementary particles and to construct its unified theory in the future. Because the neutrinos have finite masses and mixing, the neutrinos perform neutrino oscillation if their masses are not equal. For two flavor case, the probability that a particular flavor neutrino ν_x with energy E_ν to remain as ν_x after traveling the distance L becomes,

$$P_{\nu_x \rightarrow \nu_x} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}, \quad (1)$$

due to the neutrino oscillation, where, Δm^2 is the difference of the squared mass of the two mass eigen states; $m_2^2 - m_1^2$, and θ is the mixing angle. Through neutrino oscillation, it is possible to access to a very small

*The KASKA group members at the time of the conference were, N.Tamura, M.Tanimoto, H.Miyata, R.Watanabe (Niigata Univ.), Y.Sakamoto, (Rikkyo Univ.), F.Suekane, K.Inoue, T.Araki, (Tohoku Univ.), M.Kuze, (Tokyo Insititute of Technology), T.Sumiyoshi, H.Minakata, O.Yasuda and H.Sugiyama (Tokyo Metropolitan Univ.)

mass range where direct measurements are difficult to reach. Experimental studies of the neutrino oscillations have been progressing very rapidly in these days. The first firm evidence of the neutrino oscillation was discovered in the disappearance of muon type atmospheric neutrinos by SuperKamiokande group in 1998¹. Recently the K2K group is confirming the result² by observing the disappearance of ν_μ produced by the KEK-PS accelerator. These phenomena are naturally explained by the $\nu_\mu \rightarrow \nu_\tau$ oscillation and the measured oscillation parameters are $\Delta m_{23}^2 \approx 2 \times 10^{-3} eV^2$ and $\sin^2 2\theta_{23} \approx 1$. As for the electron type neutrinos there have been indications of the neutrino oscillation in the deficit of the solar neutrinos³ for long time. A transformation of the solar ν_e to other type neutrinos was identified by SNO group in 2002⁴. The KamLAND group observed a large deficit in reactor $\bar{\nu}_e$ in 2002⁵. Combined analysis shows that the oscillation parameters are $\Delta m_{12}^2 \approx 7 \times 10^{-5} eV^2$ and $\sin^2 2\theta_{12} \approx 0.8$. The remaining important subjects of the neutrino physics is to measure finite value of or to set a strong limit on the last mixing angle θ_{13} , and then to measure the leptonic CP violating phase δ_{CP} . The θ_{13} can be measured by either reactor $\bar{\nu}_e$ disappearance at the baseline around 1.5km or $\nu_\mu \rightarrow \nu_e$ appearance experiment at around $\Delta m^2 \approx 2 \times 10^{-3} eV^2$. The most stringent upper limit of θ_{13} was measured by CHOOZ group using reactor $\bar{\nu}_e$ s to be $\sin^2 2\theta_{13} < 0.2$ at $\Delta m^2 = 2 \times 10^{-3} eV^2$ ¹⁰. Long baseline accelerator experiments (LBL) which has sensitivity to θ_{13} have been approved^{6 7}. On the other hand, improving the CHOOZ limit significantly by using reactor neutrinos with near/far detector strategy had been considered by Krasnoyarsk group⁸. In late 2002, we pointed out in the paper⁹ that the reactor θ_{13} measurement is important despite some LBL θ_{13} experiments would run in the near future. The point of this paper was that if the Large Mixing Angle (LMA) solution for the solar neutrino problem is correct, the $\sin \delta_{CP}$ terms in eq.-(2) can not be ignored any more (this very reason enables the measurement of δ_{CP} in future LBL experiments) and it is difficult to extract θ_{13} information from the measurement of ν_e appearance.

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} - \frac{\pi}{2} \frac{\Delta m_{12}^2}{\Delta m_{23}^2} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin \delta_{CP} \quad (2)$$

Furthermore the degeneracy problem of θ_{23} disturbs the θ_{13} determination by LBL experiments. On the other hand the reactor based $\bar{\nu}_e$ oscillation measurement is a pure $\sin^2 2\theta_{13}$ measurement and by combining with the

LBL measurement, there is a possibility to obtain precious information such as solving such degeneracies and even obtaining a clue of non-0 δ_{CP} before the $\bar{\nu}$ operation mode of LBL experiments. A realistic idea to measure $\sin^2 2\theta_{13}$ precisely using $\bar{\nu}_e$ coming from the Kashiwazaki-Kariwa nuclear power station was also shown in the paper. Meanwhile, KamLAND showed that the LMA is the correct answer and that both Δm_{12}^2 and $\sin^2 2\theta_{12}$ are reasonably large that there is a possibility to measure $\sin \delta_{CP}$ in the future experiments. Because detectability of $\sin \delta_{CP}$ depends also on θ_{13} , the reactor $\sin^2 2\theta_{13}$ measurement became important accordingly and enthusiasm to such experiments broke out. In NOON03 (Feb. 2003), there were three talks on reactor- θ_{13} experiment from Japan¹², USA¹³ and Europe¹⁴. There have been 3 workshops dedicated to the reactor- θ_{13} within a year, in Alabama, USA (April/'03), in Munich, Germany (October/'03) and in Niigata, Japan (March/'03). There has been a lot of activities in worldwide. Along with these activities, a white paper for the reactor- θ_{13} measurement was written by 125 authors¹¹ in January, 2004. The conclusion of the white paper stresses the importance of the reactor- θ_{13} measurement and shows that it is possible to build such detectors which have sensitivity $\sin^2 2\theta_{13} = 0.02$ or better by making use of current neutrino detection technologies with a relatively short time period. The cost of this kind of experiment is small if compared with LBL experiments and these measurements can be done by very cost-effective way. Now there are 7 proposed sites all over the world; from Japan, Europe, USA, Russia, China and Brazil. The status of the Japanese KASKA project is described below.

2. KASKA experiment

KASKA is an abbreviation of *Kashiwazaki-Kariwa* Nuclear Power Station, following the tradition to name experiment after the power station to use. The Kashiwazaki-Kariwa nuclear power station, which is the world's most powerful nuclear reactor complex, has seven reactors and generates thermal energy of 24.3GW. It produces $4.4 \times 10^{22} \bar{\nu}_e$ /second when all the reactors are up. The seven reactors are arranged approximately in line forming two clusters, each consisting of 3 and 4 reactors as shown in fig.-1. In KASKA experiment, three identical neutrino detectors will be used. Two near detectors are placed at an approximate distance of 400m from corresponding cluster and the far detector is placed at the distance of 1.3km (1.8km optional) from all the reactors. By comparing the data of near-far detectors,

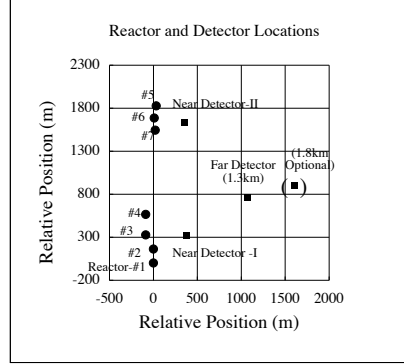


Figure 1. The reactor and planned detector positions. Kashiwazaki-Kariwa Nuclear power station consists of seven powerful reactors forming two clusters each has 4 and 3 reactors respectively. 2 near detectors are placed at around 400m from corresponding cluster. The distance between the far detector and the reactors are around 1.3km. There is an optional plan to put the detector at 1.8km.

most systematics, such as detector efficiency and neutrino flux ambiguity will cancel out. The detectors are placed deep underground using shaft holes with diameter 6m. The depth of the shaft hole is 200m (250m for 1.8km case) for far detector and 70m for two near detectors. The cosmic ray rate is estimated to be $0.35/m^2/s$ for the far detector and ten times more for the near detectors¹⁵. The cosmic-ray directly falls from the open space above the detector is only a fraction of the total cosmic-ray rate. Fig.- 2 shows the schematic view of the detector. The central part (Region-I) is 8tons of Gd loaded liquid scintillator (Gd-LS) with Gd concentration of 0.1% or more. This Gd-LS is the PaloVerde type, which is stable for at least a few years in an acrylic container¹⁶. The reactor $\bar{\nu}_e$ is detected with the following process.

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (3)$$

Then the neutron is absorbed by the Gd, producing γ -rays whose total energy amounts to 8MeV.

$$n + Gd \rightarrow Gd' + \gamma s (\sum E_\gamma = 8MeV) \quad (4)$$

By taking the coincidence of the positron and neutron signals, backgrounds are severely suppressed. 60,000events (30,000events with 1.8km baseline) will

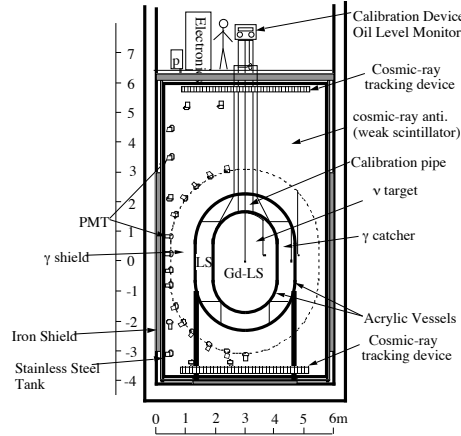


Figure 2. Schematic view of the detector. The $\bar{\nu}_e$ target is 8ton Gd loaded liquid scintillator. The Gd concentration is 0.1% or more, corresponding to the neutron absorption probability on Gd of 88% or more. The $\bar{\nu}_e$ target is surrounded by 60cm thick γ catcher scintillator. This scintillator catches γ rays which escape from the Gd loaded liquid scintillator and to reconstructs original neutron absorption and positron energy. The γ catcher scintillator is surrounded by 90cm thick buffer oil. This buffer oil shield γ -rays from PMT glass, from which CHOOZ experiments suffered much. The outer most layer is muon anti-counter made of weak scintillator to improve cosmic-ray tagging efficiency. The far detector will be placed at the bottom of 200m shaft hole with diameter 6m. The near detectors will be placed at the bottom of 70m depth shaft hole.

be collected in the far detector with three years of operation, assuming the reactor and detector efficiency to be 50%. The corresponding statistic error is 0.4% (0.6%). The near detectors will collect 600,000 events in the same period. The Gd-LS is contained in an acrylic container with the shape of two half spheres sandwiching a cylinder. The radius of the sphere and the cylinder is 1.1m. The height of the cylinder part is 1.2m and the volume is $10m^3$. The $\bar{\nu}_e$ event rate is roughly 100/day for far detector and 5 times more for each near detector. There is a normal liquid scintillator layer (Region-II) outside of the Gd-LS, having the same light output as the Gd-LS. This region is used to catch the γ -rays which escape from Region-I and to reconstruct the original energies of neutron and positron signals. The region-II scintillator is contained in the 2nd acrylic container. There are 90cm thick non-scintillating buffer oil (Region-III) between Region-II and

PMT. This layer is used to absorb the γ -rays from the PMT glass. There are 400 8 inch PMTs at the outside of the Region-III, whose photo-cathode covers 10% of total area. The glass of PMT will be a low background type. With the buffer oil, the single rate from the PMT glass will reduce to be less than 5Hz with 0.9MeV energy threshold. The outer most region (Region-IV) is the cosmic-ray anti-counter. A high efficiency of cosmic-ray anti counter is essential to reduce the cosmic-ray associated background and weak scintillator will be used. The upper part of the anti counter is made significantly thick to efficiently reduce the fast neutron background. There are cosmic-ray tracking devices at the top and bottom of the anti-counter region. The position resolution will be around 10cm, corresponding to the vertex reconstruction resolution of the neutrino events. The measured cosmic-ray track is used to estimate spallation background such as ^9Li based on distribution of the distances between the event and the track. The absolute contamination values of such correlated spallation events are expected to be order of 0.5% and can be measured to the accuracy of better than 0.3%. The spallation single events are used as the energy and position calibration. All the liquid is contained in double layers of stainless steel tank and steel tank for safety. The steel tank is also used as the geo-magnetic shield. Outside of these tanks, there is thick iron layers to shield gamma rays from the soils outside. The nature of the soil around the detector is a watery mud of density of 1.75g/cc. This low density and high water component are expected to help to reduce the fast neutron background. At the top of the detector there will be additional thick iron layer to absorb hadronic and soft components of the cosmic rays which come directly from the open shaft area at the top. The readout electronics is being designed based on 500MHz-10bit flash ADC and FPGA.

Because the single background rate will be only a few Hz at 1MeV positron threshold and less than 0.01Hz for 4MeV neutron threshold, the accidental background is less than 1% and this can be precisely measured by shifting the coincidence window. The main background will be fast neutrons. The absolute amount of the neutron background is expected to be 1% and it can be measured with precision of 20% using the prompt energy spectrum at above the reactor $\bar{\nu}_e$ range.

The event selections are simple. (1) $0.9\text{MeV} < E_{\text{prompt}}$, (2) $4\text{MeV} < E_{\text{delayed}}$ and (3) $1\mu\text{s} < t_{\text{delay}} - t_{\text{prompt}} < 200\mu\text{s}$. Because the prompt signal energy is larger than 1.022MeV, and the delayed energy peaks at 8MeV, the selection (1) and (2) are insensitive to the energy calibration error. The neutron capture signal on ^{12}C ($E=4.95\text{MeV}$, 0.05% of neutron absorption)

can be used as an energy calibration point for the cut (2). The selection (3) makes use of relative timing and can be performed precisely. Because there is no fiducial cut, it is free from the error associating with position reconstruction.

The main error of the neutrino detection efficiency comes from the relative difference of the volume of the Gd-LS between the detectors. The volume will not be defined by the container volume because it possibly deforms under the pressure of the liquids. But it will be defined by the volume of the LS which is measured precisely when introducing in the detector. The expected accuracy of the measurement will be 0.5% or better.

Since there are significant improvements of the detector from CHOOZ experiment, whose detector associated error is 1.5%, we anticipate the absolute error of single KASKA detector can be 1% or less. By comparing near and far detectors most of the remaining systematics and ambiguities associated to the neutrino flux cancel and the final systematic error is expected to be much better than 1%. Fig.-3 shows the expected near/far sensitivity after 3 years of operation for the cases of 1% and 0.5% of systematic errors and 1.3km and 1.8km baselines. It is possible to improve the sensitivity down to $\sin^2 2\theta_{13} = 0.017 \sim 0.027$.

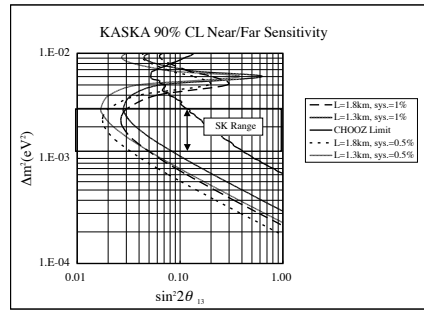


Figure 3. KASKA 90 % C.L. sensitivity for the case of far detector locations of 1.3km and 1.8km and the systematic uncertainty of 0.5% and 1%. The average distance of the near detectors is 400m. The recent SuperKamiokande results of atmospheric neutrino oscillation. The dip at $\Delta m^2 \approx 6 \times 10^{-3} eV^2$ is due to the fact that the disappearance rate at near and far detectors become same at this Δm^2 . In the actual analysis, the limit of this region is governed by the absolute systematic error of the detection efficiency and there will not be such deep valley.

3. Summary

Now it can be said that it is consensus among the neutrino physicists that the reactor- θ_{13} measurement is important. The KASKA experiment will measure the last neutrino mixing angle $\sin^2 2\theta_{13}$ with 90%C.L. accuracy of $0.017 \sim 0.027$ using reactor $\bar{\nu}_e$. The reactor measurement of $\sin^2 2\theta_{13}$ with this sensitivity is important because if finite $\sin^2 2\theta_{13}$ is observed by this experiment, it means that there is a good chance to observe $\sin \delta_{CP}$ in future experiments. If $\sin^2 2\theta_{13}$ is too small to be detected by this experiment, probably it will become necessary to perform another set of reactor- θ_{13} experiments with higher sensitivity before LBL experiments to detect CP violation, to check if there is still possibility to measure $\sin \delta_{CP}$ in such experiments. Also it means that the ν_3 component of the ν_e is really small unlike other neutrino mixing, and exploring the reason of this smallness may play a key roll when constructing the unified theory of the elementary particles.

The conceptual design of the KASKA detectors is almost complete and negotiations with the electric power company and various administrative organs are progressing well. Recently, detector R&D funds are approved and we are hoping that the project is approved in the near future.

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